RANIOPHARYNGIOMAS are extraaxial epithelial tumors (World Health Organization Grade 1) that arise from remnants of the craniopharyngeal duct or Rathke pouch. These are relatively uncommon tumors, accounting for not more than 5% of all intracranial tumors, or up to 10% of brain tumors in children. The incidence of craniopharyngioma has been estimated at ~1.5 cases per million people per year, but may be considerably higher among members of specific ethnic groups, such as Japanese children (5.25 per million). There is a bimodal age distribution for this lesion, with peak rates in children 5–14 years of age and in adults 50–74 years of age. Management of craniopharyngiomas remains a challenge because of the location of this tumor and its intimate relationship with surrounding eloquent structures such as the optic apparatus, the hypothalamus, the pituitary gland, and the carotid arteries. Patients frequently present with visual disturbances and endocrine deficiencies because of the lesion’s proximity to these structures. Involvement of the third ventricle can also lead to signs and symptoms of raised intracranial pressure from obstructive hydrocephalus. The treatment strategies usually considered involve either GTR or limited resection followed by radiation therapy. Other important treatment strategies that may be appropriate include cyst drainage and chemotherapy with bleomycin.

The clinical state of the patient, the anatomy of the tumor, and the expertise of the surgeon determine the choice of treatment; often a multimodal approach is the most appropriate. Whichever strategy is considered must be balanced against the risk of harming the surrounding eloquent structures. If it can be safely performed with minimal risk to these structures, GTR remains the treatment of choice as...
this allows rapid decompression, minimizes the risk of recurrence, and provides a specimen for histological diagnosis. However, judgment of minimal risk is often not clear-cut. Some surgeons favor STR coupled with adjunctive therapy to achieve the same goals.\textsuperscript{6,10,19,20,22,24,47,48,55} Recurrent craniopharyngiomas must be considered separately because repeated surgery is associated with a higher risk of complications and a lower cure rate.\textsuperscript{5,10,12,14,15,53}

Comparing surgical complication rates across different case series produces a variable picture. The authors of most of the recent large series report a total resection rate of 27–90%.\textsuperscript{10,18,31,54} Reported surgical mortality rates vary from 1.1 to 3.9%.\textsuperscript{10,45,51,54} However, without doubt, recurrent tumors are associated with significantly higher risks and poorer outcome, with overall mortality rates of 10.5–40.6%.\textsuperscript{10,54} It is also difficult to compare complication rates between series. Pituitary dysfunction may occur in 50–100% of patients, the most common form being diabetes insipidus. Visual deterioration may occur in up to 50% of patients who undergo GTR.

Radiation Therapy for Craniopharyngiomas

Although resection may be the primary treatment modality initially, craniopharyngiomas are difficult to cure with surgery alone. It has long been established that radiation therapy is effective against craniopharyngiomas,\textsuperscript{30} and it has become a standard of treatment for residual or recurrent craniopharyngiomas. The results of most case series have shown that after STR, adjuvant radiotherapy allows greater tumor control and a better survival rate than surgery alone (40 vs 90%, 10-year progression-free survival).\textsuperscript{15,17,40,41,46,52} The case for primary radiation therapy for recurrent craniopharyngiomas is even stronger in terms of lower risk and better outcome, with 10-year progression-free survival in 30% of surgical patients and in 90% of those who underwent radiosurgery.\textsuperscript{23–25,36}

The main strategy for maximizing effectiveness and minimizing the damage caused by radiation therapy is to deliver the radiation accurately while sparing surrounding normal structures and to optimize the radiation dosing scheme. Various means of achieving this include conformal radiotherapy, intensity modulated radiotherapy, stereotactic radiotherapy, and SRS. Stereotactic intracavitary radiotherapy with \(^{90}\text{Y}\) or \(^{32}\text{P}\) is also used, especially as a primary treatment of cystic tumors or as an adjuvant treatment after surgery or radiotherapy.

However, conventionally fractionated focal radiation therapy around the sellar and suprasellar region is also associated with risks similar to those of surgery. Both treatments can cause pituitary dysfunction (diabetes insipidus, panhypopituitarism, and hypogonadism), hypothalamic dysfunction (hypothalamic obesity and sleep disturbances), and visual and cognitive deterioration. Radiation therapy carries the additional risk of radiation-induced necrosis, secondary malignancies, and vasculopathy. The normal optic apparatus is particularly sensitive to radiation, and even with optimized dose and fractionation regimens, there is a \(\sim 3\%\) risk of optic neuropathy.\textsuperscript{15,34,37} Delayed pituitary failure after regional radiation therapy has also been well described and may occur in 30–70% of patients who receive conventional radiotherapy.\textsuperscript{2,9,33} Other complications include secondary malignancies\textsuperscript{6,42,49} and temporal lobe necrosis.\textsuperscript{21,49}

Stereotactic Radiosurgery and Radiotherapy

Stereotaxy in radiotherapy allows accurate localization of the lesion so that a radiation beam can be targeted to the lesion while sparing the surrounding structures. Most stereotactic systems can deliver a radiation beam to within \(\sim 1\) mm of the lesion. Such accuracy means that a very high dose of radiation can be given as a single delivery to obliterate the tumor (SRS). However, some of the controversy surrounding the application of radiation therapy to craniopharyngiomas relates to the optimal dosing so that risks to the optic apparatus and pituitary gland are minimized. Is a focal single fraction radiotherapy dose better than a fractionated dose in a situation where the optic apparatus or pituitary gland is close to the lesion? Conventional fractionated radiotherapy can also be delivered by stereotactic means (stereotactic radiotherapy), thereby combining the advantages of fractionation with the accuracy of radiosurgery. Long-term results are still needed to see if stereotactic radiotherapy will indeed decrease the risk of damage to the surrounding structures and improve functional outcome.\textsuperscript{36,43,44}

Stereotactic radiosurgical treatment of craniopharyngiomas is typically limited to tumors 3 cm or smaller that are 3–5 mm away from the optic chiasm and nerves. The authors of several studies have reported safe and effective long-term results with the Gamma Knife in the treatment of craniopharyngiomas.\textsuperscript{7,28,44,50} The CyberKnife (Accuray, Inc.) consists of a miniature lightweight linear accelerator mounted on a robotic arm with 6 degrees of freedom of movement. This allows unobstructed access to the entire body, and a photon beam can be targeted with submillimeter accuracy. The device uses an image-guided control loop with target tracking capabilities that can adjust to patient movements, thus obviating the use of invasive frames to stabilize the patient. In the present study we report the first series of the treatment of residual craniopharyngiomas situated within 2 mm of the optic apparatus or pituitary gland.

Clinical Materials and Methods

Sixteen patients with confirmed, previously resected craniopharyngiomas underwent SRS with the CyberKnife at Stanford University Medical Center between November 2000 and November 2007 (Fig. 1). A retrospective review of these cases was undertaken by obtaining clinical information from an institutional review board–approved prospective database. Each patient was evaluated by the neuroendocrinologist and neuroophthalmologist before and after SRS. A multidisciplinary team of neurosurgeons, radiation oncologists, and neuroradiologists evaluated each patient for treatment eligibility. Informed consent was obtained from each patient before enrollment in this institutional review board–approved clinical study.

Radiosurgical Treatment Planning

The lesions in each patient were evaluated on 1–25 mm contiguous slice, high-resolution CT images, with and without contrast enhancement (iohexol, 350 mg/ml; Nycomed, Inc.) with either a GE Light Speed 8i or 16i unit. In most cases, thin-section MR images were also obtained. The image data were transferred to the CyberKnife work-
station and the treating surgeon manually outlined the target volume and critical structures on the axial images using proprietary MultiPlan and InView software (Figs. 2 and 3). Simultaneous overlay of these contours on coronal and sagittal reconstructions was performed. In most cases, the noneffaced anterior visual pathways, including the optic nerves and chiasm, could be readily delineated, especially when an MR–CT fusion was performed. At times, however, portions of the optic apparatus could not be delineated with confidence because the tumor obscured or displaced a segment.

**Radiation Dose Selection**

In the present study, all treatment plans were designed using an inverse planning algorithm that involved setting dose constraints to minimize irradiation of specified structures such as the optic apparatus and maximize doses to the tumor. The neurosurgeon and radiation oncologist jointly determined the marginal and maximal doses, as well as the number of sessions. When delineation of the optic apparatus was clear, exposure to these critical structures was limited to < 5 Gy per session. However, when the delineation of these structures was not clear, it was not possible to meet the exposure limit.

All patients received treatments in multiple sessions, ranging from 3 to 10 sessions, to a mean target volume of 6 cm³ (range 0.3–26.3 cm³), using a mean marginal dose of 21.6 Gy (range 18–38 Gy) prescribed to a mean isodose line of 75% (range 67–80%). The mean maximum dose was 29.9 Gy (range 24.1–42.1 Gy).

**Treatment Delivery**

Patients were placed supine on the treatment couch and fitted with a previously constructed custom thermoplastic mask. Once the patient’s position was registered, the radiation was delivered. After the completion of each session, patients received 4–8 mg of dexamethasone orally. The sessions were 12–24 hours apart.

**Evaluation of Patient Outcomes**

After SRS with the CyberKnife, all patients underwent clinical and radiological evaluation by a team consisting of neurosurgeons, radiation oncologists, neuroendocrinologists, neuroophthalmologists, and neuroradiologists. Magnetic resonance imaging and formal Goldman visual field assessments were performed at 6-month intervals for 2 years, then once every year. Patients who attended follow-up at outside institutions had their clinical reports, visual assessments, and imaging sent to us for review. The formula for an idealized ellipsoid (volume = 4/3 π (length/2 × width/2 × height/2)) was used to estimate the tumor volume on pre- and posttreatment MR images.

**Results**

**Patient Characteristics**

Over an 8-year period, 16 patients were identified who had residual or recurrent craniopharyngiomas and were treated with CyberKnife radiosurgery. The patient characteristics are summarized in Table 1. Five of 16 patients...
(Cases 12–16) were excluded from the study either because of missing clinical data or insufficient follow-up. The mean age at treatment for the 11 included patients was 34.5 years (range 13–71 years). There were 5 men and 6 women. All patients initially presented with symptoms or signs attributable to the tumor. Ten of 11 had some degree of visual field loss. Only 1 patient (Case 7) did not experience visual disturbances. Five of 11 had endocrine abnormalities that required hormonal replacement. All patients underwent resection, and histological testing of the specimen confirmed the diagnosis of craniopharyngioma. Ten patients had operative reports documenting an STR with radiological confirmation. One patient underwent a complete resection, but follow-up MR images revealed a recurrence 1 year after surgery (Case 3). Four patients underwent 1 surgical procedure, 4 underwent 2 procedures, and 3 patients had 3 procedures. One patient received a 54-Gy dose of radiotherapy after the first surgery before presenting again 4 years later with worsening symptoms (Case 2). This patient underwent a second operation and then CyberKnife SRS. In 9 patients, the symptoms improved after surgery, but 2 experienced worsened visual field deficits prior to SRS.

In most cases, the residual tumor was located in the suprasellar region, and in 10 cases it was found to be against or displacing the optic nerve or chiasm. The pituitary stalk alone was compressed in 1 patient.

**CyberKnife Treatment**

All patients had multisession CyberKnife SRS. Three patients had 3 sessions, 1 had 4 sessions, and 6 had 5 sessions. Due to the large size of the recurrent tumor and its proximity to critical structures, radiotherapy to 1 patient was administered over 10 sessions, which may be classified as stereotactic radiotherapy rather than radiosurgery. There were no acute complications in any of the patients.

**Treatment Outcomes**

The mean follow-up time was 15.4 months (range 4–64 months). All 10 patients with visual field or acuity prob-
Multisession CyberKnife radiosurgery for residual craniopharyngiomas

TABLE 1
Summary of characteristics of patients who underwent CyberKnife SRS for residual craniopharyngiomas, 2000–2007*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Presentation</th>
<th>No. of Ops</th>
<th>Pre-SRS Postop Visual Problems</th>
<th>Pre-SRS Endocrine Problems</th>
<th>No. of Fractions</th>
<th>Treatment Dose (Gy)</th>
<th>Mean Isodose Line (%)</th>
<th>Max Dose (Gy)</th>
<th>Target Volume (cm³)</th>
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<td>26.6</td>
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<td>69</td>
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<td>5</td>
<td>27.5</td>
<td>70</td>
<td>39.3</td>
<td>5.6</td>
</tr>
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</table>

* The patients in Cases 12–16 were excluded from the analysis either due to missing clinical data or inadequate follow-up time.

† This patient underwent stereotactic radiotherapy.

Discussion

The propensity of craniopharyngiomas to be closely associated with neurovascular structures of the parasellar region makes this benign tumor a neurosurgical challenge and far from “benign” for the patient. Often only STR is possible without causing further harm to the patient. The residual tumor is frequently stuck to or displaces the optic apparatus, pituitary gland, and other important parasellar structures. Because many patients will already have impaired vision, saving the residual visual function becomes even more important. Microsurgery has an important role in the rapid decompression of these critical structures, sometimes even offering the chance of a cure. However, leaving residual tumor around structures such as the optic nerves or chiasm is inevitable in many cases. Recurrent tumors and patients who are poor surgical candidates may also limit the role of surgery. The 2 main alternative treatments to surgery are single-session SRS or conventional fractionated radiotherapy.

Radiosurgery has proven to be very effective in many benign intracranial tumors.¹ However, some studies have shown that injury to the optic nerve or chiasm may occur if >8–10 Gy is delivered in a single fraction to a segment of the optic apparatus.¹³,²² while in another study craniopharyngiomas were successfully treated with a limit of 13 Gy to the optic apparatus.²⁹ In general, however, radiosurgery is contraindicated if the distance between the tumor and optic apparatus is <3 mm because the visual pathways would typically receive >10 Gy at these situations.

In these periorbital lesions, the tradition has been to use conventional fractionated radiotherapy. Fractionation is a fundamental principle of radiation therapy and has biological advantages that allow recovery of normal adjacent tissue. Typically, benign lesions are treated with doses of 45–55 Gy in 1.8–2 Gy fractions to prevent growth of tumor and minimize injury to the visual pathways. Long-term (10 year) local tumor control ranges from 31 to 42% for patients treated with surgery alone compared with 57–89% in those treated with surgery and radiotherapy.¹,¹³,¹⁷,³⁹,⁴¹,⁴⁶,⁵² However, there are limitations to its use, as the wide treatment field includes many structures including the optic apparatus, pituitary gland, hypothalamus, and medial temporal lobe that could all receive radiation. Subsequent injury to these structures, radiation necrosis, and secondary malignant changes can occasionally occur. The risk may only manifest itself after a long delay, but this is particularly important because benign conditions like craniopharyngiomas have good long-term survival prospects and many patients with these lesions are young. Another limitation is that when conventional radiotherapy fails, it almost inevitably precludes further radiotherapy treatment to the recurrent tumor. Finally, although of minor importance, conventional fractionated radiotherapy usually takes place over a 6-week course, which is less attractive to patients than other shorter treatment courses.

The tolerance of critical neurovascular structures to rad-
ation depends on a multitude of factors including the amount of radiation received, the volume of tissue irradiated, and any prior injury or radiotherapy to the area. With the availability of image-guided radiosurgical technology, the principle of multisession delivery of radiosurgery can be incorporated with the anatomic precision and conformality of radiosurgery. This allows the precise delivery of lower and safer radiation doses than those used in single-sesion radiosurgery, while at the same time exploiting the volume effect by applying higher and more effective doses than was possible with conventional radiation therapy. In this series, treatment plans were designed to keep the dose to the optic apparatus < 5 Gy during any single session. The volume of the optic apparatus that received 80% of the prescribed dose was < 0.05 cm³, whereas the volume that received 50% of the dose was < 0.5 cm³. Therefore, the actual volume of the optic segment that received 5 Gy would be small relative to the total volume of the optic apparatus.

In the present study, we have shown that radiosurgery delivered with the CyberKnife is an effective adjuvant therapy after surgery for residual craniopharyngiomas. Tumor control or shrinkage without any neuroendocrine or visual complications was achieved in 10 (91%) of 11 patients. We delivered a multisession treatment regimen, which minimized the risk to the optic apparatus and pituitary gland. Moreover, a nonisocentric treatment plan was used successfully, which improved dose homogeneity and thereby reduced dosing hotspots on structures such as the optic nerves and chiasm. None of the patients required additional hormonal therapy. Preservation of baseline visual function is supported by our previous work, which also showed that the risk of visual loss with multisession radiosurgery appears to be low for periorbital tumors.1,3,8 Radiation-induced optic neuropathy may take several years to develop, but it usually occurs within the first 24 months after irradiation. However, a limitation of our study is the relatively short follow-up period and small number of patients. Although none of the patients in the present study had worsening visual acuity or visual fields, definitive conclusions regarding the safety of multisession CyberKnife SRS cannot be reached. The selection of doses and number of sessions have also been derived empirically and from experience with other radiotherapy and frame-based radiosurgical procedures. Again, in the absence of Class 1 studies, the optimal dose and number of sessions for individual patients are still not known. In 1 case, cystic enlargement occurred after CyberKnife treatment. It is known that irradiation of cystic craniopharyngiomas may result in cystic enlargement, which does not represent tumor recurrence, and may later regress.3 The patient’s symptoms remained stable, but it is important that these patients continue to undergo clinical and radiological follow-up and visual and neuroendocrine assessment as appropriate. A larger numbers of patients with longer follow-up periods are required to evaluate the safety and effectiveness of this treatment modality fully.

Conclusions

Craniopharyngioma is a benign tumor that frequently involves the eloquent structures of the sellar and suprasellar regions. The optimal treatment strategy for craniopharyngiomas remains controversial. However, due to the high surgical risk and tendency for recurrence in STR, an individualized multimodal treatment strategy must be used to optimize outcome. Radiotherapy has a definitive role both as an adjuvant therapy after primary STR and also as a primary treatment for recurrent disease. The multisession capability of the CyberKnife allows treatment of craniopharyngiomas adjacent to the optic nerve and is effective in tumor control and shrinkage while preserving the function of nearby structures, such as the optic apparatus and pituitary gland. The avoidance of the need for rigid head fixation is particularly advantageous in pediatric patients.

Disclosure

Dr. Adler is on the board of directors of Accuray, Inc., and Drs. Adler and Chang are both shareholders of Accuray, Inc.

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